

# Chain Galaxies in the Tadpole ACS Field

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## ABSTRACT

Colors and magnitudes were determined for 69 chain galaxies, 58 other linear structures, 32 normal edge-on galaxies, and all of their large star formation clumps in the HST ACS field of the Tadpole galaxy. Redshifts of 0.5 to 2 are inferred from comparisons with published color-evolution models. The linear galaxies have no red nuclear bulges like the normal disk galaxies in our field, but the star formation clumps in each have about the same colors and magnitudes. Light profiles along the linear galaxies tend to be flat, unlike the exponential profiles of normal galaxies. Although the most extreme of the linear objects look like beaded filaments, they are all probably edge-on disks that will evolve to late Hubble type galaxies. The lack of an exponential profile is either the result of a dust scale height that is comparable to the stellar scale height, or an intrinsically irregular structure. Examples of galaxies that could be face-on versions of linear galaxies are shown. They have an irregular clumpy structure with no central bulge and with clump colors and magnitudes that are comparable to those in the linears. Radiative transfer solutions to the magnitudes and surface brightnesses of inclined dusty galaxies suggest that edge-on disks should become more prominent near the detection limit for surface brightness. The surface brightness distribution of the edge-on galaxies in this field confirm this selection effect. The star formation regions are much more massive than in modern galaxies, averaging up to  $\sim 10^9 M_\odot$  for kpc scales.

*Subject headings:* galaxies: evolution — galaxies: structure

## 1. Introduction

Recent high resolution deep optical imaging of regions such as the Hubble Deep Field North (HDF-N; Williams et al. 1996) and South (HDF-S; Volonteri, Saracco, & Chincarini 2000) and the Hawaiian Deep Field (Cowie, Hu, & Songaila 1995) has enabled the study of large samples of non-local galaxies. Such fields showed that galaxies with  $z > 0.5$  can have non-standard morphologies (van den Bergh et al. 2000). The most linear have been called chain galaxies (Cowie et al. 1995; van den Bergh et al. 1996), while head-tail galaxies have been called tadpoles. Such objects may be transient peculiar objects (Taniguchi & Shioya 2001) or an early stage of normal galaxy evolution (Cowie et al. 1995). Previous studies measured typical apparent I-band magnitudes of  $\sim 24.5$  mag and went as faint as  $I = 27$  mag (Lilly, Cowie, & Gardner 1991). Here we present photometric and structural measurements of 127 linear objects out to 27 mag using the Hubble Space Telescope (HST) field of the Tadpole galaxy (UGC 10214).

## 2. Data and Analysis

Deep images of UGC 10214 were obtained with the Advanced Camera for Surveys (ACS) on HST in April 2002 (Tran et al. 2003). The Wide Field Channel (WFC) provides a field of view of 3.4 arcmin  $\times$  3.4 arcmin with 0.05 arcsec resolution and the combined images measure 3.9 arcmin  $\times$  4.2 arcmin. The exposure times were 13600 s in the F475W filter (g band), 8040 s in the F606W filter (broad V band) and 8180 s in the F814W filter (I band). The images were kindly made available in advance of publication in fully reduced form by the ACS team, using the methods of Blakeslee et al. (2003) and Tran et al. (2003) but with more up-to-date reference files and a new damped sinc ('lanczos3') drizzling kernel for improved resolution over what is available in the Early Release Observations (ERO) on the public website. Figure 1 shows a 1 arcmin  $\times$  1 arcmin portion of the ACS field.

Linear objects in the field were grouped into four morphological categories: chain, having linear and clumpy structures (seen in Figure 1); double, having two big clumps; tadpole, having a head and tail shape, and normal, for edge-on spiral galaxies with distinct bulges and occasional midplane dust lanes and clumps. Representative objects are shown in Figure 2, with V-band grayscale images and contours. The contours are in linear increments; the lowest contour level is  $1\sigma$  of the pixel noise, which corresponds to a surface brightness of  $25.5$  mag arcsec $^{-2}$ .

The axial ratios of the objects were determined by measuring lengths and widths from contour plots at a contour level  $2\sigma$ , corresponding to a surface brightness of 24.75 mag

arcsec<sup>-2</sup>. The chain, double, tadpole and normal galaxy objects have average axial ratios of  $5.1 \pm 2.0$ ,  $4.0 \pm 1.5$ ,  $3.7 \pm 1.8$ , and  $3.2 \pm 1.0$ , respectively.

Total integrated magnitudes were determined in all three filters and converted to the AB magnitude system, in which a galaxy with a flat spectrum has equal magnitudes in each passband. We used  $m = -2.5 \log(\text{counts}/\text{exposure time}) + \text{zeropoint}$ , with the following zeropoints (see Blakeslee et al. 2003): 26.045 for g band, 26.493 for V band, and 25.921 for I band. Magnitudes were determined from counts within a box outlining each object, based on contour plots where the lowest contour is  $1\sigma$ . Boxes were selected to be 5 pixels wider than the outer contours of the objects, based on an examination of the turnover point on a plot of magnitude as a function of box size.

The chain galaxies range from I=22 to I=27 mag, with six fainter than 26 mag. For comparison, the Cowie et al. survey of the Hawaiian deep fields was complete to about I=26 mag, and all 25 of their chain galaxies had magnitudes between I=22 and I=25. The only objects brighter than I=22 mag in our sample are normal edge-on spiral galaxies.

Radial profiles were made along the major axis of each object using strips 7 pixels wide. Sample profiles for g, V, and I band intensity and (V-I) color are shown in Figure 3. The objects that look like normal edge-on galaxies have exponential profiles with central bulges. Chain galaxies, doubles, and tadpoles of the same apparent size and magnitude as normals have neither exponential profiles nor prominent bulges. Their interclump profiles are nearly flat, and their clumps have similar brightnesses and colors with no bright red object that could be a bulge (see also Cowie et al. 1995, Figure 22).

Vertical marker lines in Figure 3 connect the intensity peaks in the top part of the figure with color features in the bottom part. The central peak in the normal galaxy is  $\sim 0.5$  mag redder than its surroundings, while most of the peaks in the chain, double, and tadpole objects are  $\sim 0.2$  mag bluer than their surroundings. The normal galaxy also has a blue off-center clump.

In Figure 4 (top), color-color diagrams are shown for the integrated light of all of the galaxies. The chain, double, and tadpole galaxies fill the same blue region of the diagram. Some of the normal galaxies are also blue, while others are red. Morphologically, the normal galaxies all appear similar, with a central bulge and an exponential disk. It is possible that the redder normals are earlier-type galaxies and the blue ones are later type. There could also be a blueing effect with distance (e.g., Lilly et al. 1991), assuming the smaller and bluer galaxies are more distant on average. The crosses are not linear galaxies like the rest but are clusters of clumps that could be face-on versions of the linear galaxies, as discussed in Section 4.

Figure 4 (bottom) shows the distribution of color for all of the clumps in 8 representative chain galaxies (open symbols) and 7 representative normal edge-on galaxies (filled symbols). Double, tadpole, and all of the other chain galaxies in our study have similar clump colors and are not plotted to avoid confusion. The triangles in the figure are integrated magnitudes, the circles are non-central clumps, and the squares are central clumps. The central clumps of the normal edge-on galaxies are red with  $(V-I) > 1$ ; they are probably normal bulges. The non-central clumps in all of the galaxies and the central clumps in the chain galaxies are all somewhat blue and are most likely regions of recent or active star-formation. Clump clusters are also shown as cross and plus symbols.

The surface brightnesses of the galaxies were determined from their isophotal magnitudes and their sizes based on contour plots. For chains, doubles, and tadpoles, the average I-band surface brightnesses are  $23.43 \pm 0.83$ ,  $23.28 \pm 0.66$ , and  $23.55 \pm 0.54$  mag arcsec $^{-2}$ , respectively, while for normal edge-on galaxies the average is slightly brighter,  $22.91 \pm 0.91$ . Figure 5 shows the distribution of surface brightness for all of the galaxies. The vertical line is the  $3\sigma$  detection limit, taken to be 3 times the rms deviation of a Gaussian fit to the pixel noise in a relatively blank  $100 \times 100$  pixel field of view. The count of galaxies begins to drop as the surface brightness limit is approached, suggesting there are many more galaxies that could not be detected. However, the dominance of the linear galaxies approaching this limit also suggests this peculiar class might be only the brightest members in a distribution of normal galaxies, selected preferentially here because they are edge-on. A radiative transfer model in Section 4 supports this possibility: face-on versions of the same galaxies would be fainter and not so easily detected. The two crosses in this figure are candidates for face-on versions, shown later in Figure 9; they are indeed very low in average surface brightness.

The I-band apparent magnitude distributions of the whole galaxies are shown in the top of Figure 6, and the I band magnitude distributions of the individual clumps are shown in the bottom. For the clumps, the number distributions peak at the same magnitude for the chain, double, and tadpole galaxies and for the non-central clumps in the normal galaxies, whereas the central clumps (bulges) in the normal galaxies are  $\sim 3 - 4$  mag brighter than the rest. This result again suggests that all of the clumps in chain, double, and tadpole galaxies and the non-central clumps in normal galaxies are similar. The clumps in the clump clusters are similar too. The central clumps in chain galaxies are not bulges because they have the same blue colors and the same faint magnitudes as the other clumps in these galaxies. The whole galaxies are brighter than the clumps by  $\sim 3$  magnitudes, and the normal edge-on galaxies are brighter than the chain, double and tadpole galaxies by  $\sim 2$  magnitudes, although there is a faint tail of normal galaxies that extends to the realm of the chains ( $\sim 25$ th mag). The average magnitude of a chain, double or tadpole galaxy is comparable to the average magnitude of a normal galaxy bulge.

The fraction of galaxies of each morphological type is shown in Figure 7 as a function of I-band magnitude. Normal galaxies dominate the sample out to magnitude 24. Chain galaxies dominate at fainter magnitudes and eventually account for about 40% of the sample. The fractions of each type are fairly constant beyond magnitude 24.

Scaling the number of galaxies in our field to a square degree, there are  $1.5 \times 10^4$  chain galaxies per square degree, 9300 doubles, 3200 tadpoles, and 6800 normal galaxies out to our limit of 27th mag. For comparison, Lilly et al. (1991) count in the HDF  $2.5 \times 10^5$  galaxies per square degree out to 27th mag, or  $10^5$  galaxies per square degree out to 26th mag (consistent with the B band galaxy counts in another field by Metcalfe et al. 1995). Thus  $\sim 6\%$  of galaxies out to 27th mag should be chains. For our normal edge-on galaxies, we see the equivalent of 6000 galaxies per square degree out to 25th mag, whereas Lilly et al. give  $3 \times 10^4$  galaxies per square degree of all inclinations and types to that magnitude. That means about 20% of their sample should be normal galaxies seen edge-on.

Westera et al. (2002) modeled the z-dependence of the observed color and magnitude of a hierarchically accreting protogalaxy. We infer from their Figures 1 and 8 that all of our objects, including the normal galaxies, have total stellar masses of  $\sim 10^{10} M_\odot$  and that the individual clumps have masses less than or comparable to  $\sim 10^9 M_\odot$ . The angular sizes of the chain galaxies are  $\sim 1$  arcsec, which corresponds to  $\sim 5$  kpc if the redshift is  $z \sim 1$ . Thus, the chain, double, and tadpole galaxies could all be normal late-type disk protogalaxies, viewed edge-on and possibly interacting (for the tadpoles), and with a few very massive star-formation clumps and no old central bulge.

### 3. Comparison with other Work

The chain galaxies in our sample resemble some of the chain galaxies previously reported in other fields, such as object SSA22-16 in Cowie et al. (1995) and object HDF 3-531 in van den Bergh et al. (1996). Koo et al. (1996) obtained spectra for 3 chain galaxies in their field studies; they had I magnitudes of 23.5 to 23.7 mag and redshifts from 0.8 to 1.2. The I magnitudes of our chain galaxies range from 22 to 27, with the majority fainter than 25, so our galaxies may be mostly beyond  $z=1$ . Consistent with this result is the observation that the HST Medium Deep Survey (Abraham et al. 1996) had very few chain galaxies at  $I < 22$  mag. The evolutionary models by Cowie, et al. (1996) for B magnitude as a function of redshift also suggest that our redshifts are between 1 and 2. Koo et al.'s plot of (V-I) versus redshift as a function of galaxy type suggests that our chain, tadpole, and double galaxies are in the color realm of late-type spirals between  $z=1$  and 2 (V-I = 0.3 for Sm galaxies at  $z=1.5$  to 2, or V-I = 0.9 for Sbc in that  $z$  range). This conclusion is also consistent with the

plot of absolute I mag vs.  $z$  for different apparent magnitudes as a function of galaxy type by Aguerri & Trujillo (2002). Thus, the integrated colors and magnitudes of chain galaxies are consistent with expectations for young normal galaxies at  $z \sim 1 - 2$ .

The linear objects in our study do not have exponential disks and are therefore not like nearby late-type edge-on spirals. For example, the low surface brightness galaxy UGC7321 is an edge-on galaxy with no apparent bulge, but it has an obvious exponential disk (Pohlen et al. 2003). Some faint edge-on and face-on field galaxies at  $z = 0.5$  to  $1.5$  also have exponential profiles (O’Neil, Bothun, & Impey 2000).

Our chain galaxies could be more irregular edge-on low surface brightness (LSB) galaxies (Dalcanton & Schectman 1996). The surface brightness in the center of an LSB galaxy is  $\sim 23.4$  mag arcsec $^{-2}$  (McGaugh & Bothun 1994), and midway out in the disk it is 24.5 to 25.5 mag arcsec $^{-2}$ . Our chain galaxies have surface brightnesses midway out that are 23.5 to 24 mag arcsec $^{-2}$ , which is about the same as our normal galaxies and  $\sim 1$  mag brighter than an LSB galaxy. However, an edge-on LSB galaxy should be brighter than a face-on LSB galaxy by more than a magnitude per arcsec $^2$ , as shown in section 4 below, so the irregular-LSB explanation is possible.

A chain galaxy studied by Steidel et al. (1996), C4-06, has an isophotal AB magnitude of 23.48 and an aspect ratio of 5:1, making it similar to those studied here. The redshift of C4-06 is 2.8, and it has very strong absorption lines that match those of a redshifted spectrum of the starburst galaxy NGC 4214. Unfortunately, the spectrum was too faint to detect rotation.

The structure of our chain galaxies resembles the beaded filaments seen in N-body simulations of the early universe and of globular cluster formation at  $z=4$  and  $7$  (Kravtsov & Gnedin 2003), as well as some chains of galaxies imaged by Vorontsov-Velyaminov (1977; e.g. VV144=Arp 151 at  $z=0.02$ ) and Hickson (1993, see also Mendes de Oliveira & Hickson 1994). However, the mass and size of a globular cluster is small for our clumps and the chains of galaxies in Vorontsov-Velyaminov are too large for our systems.

Reshetnikov, Dettmar, & Combes (2003) measured the length/width ratios and radial and vertical profiles for a sample of 34 edge-on galaxies in the Hubble Deep Field (HDF). They found that galaxies at  $z \sim 1$  have average major/minor axial ratios of 3.3 and concluded that the disks were about 1.5 times thicker than in local galaxies. Half of their sample, including some face-on galaxies, had non-exponential radial profiles as if they were still in the process of disk formation. This conclusion is consistent with galaxy evolution models, which show that disks may not start to develop exponential radial profiles until  $1 < z < 2$  (Westera et al. 2002). However, in most of the HDF edge-on galaxies, a central bulge-like

peak is prominent even if the disk is not yet exponential. This differs from our chain galaxies, which do not generally have central peaks. The Reshetnikov et al. edge-on galaxies also differ in axial ratio from our chain galaxies, which are about a factor of 2 thinner, although the normal edge-on galaxies in our sample have the same axial ratio as in Reshetnikov et al.. The sizes of galaxies in the two samples are about the same: Reshetnikov et al. consider galaxies with diameters larger than 1.3 arcsec, and this is the average size of our chain galaxies. Our doubles and tadpoles are slightly smaller, averaging 1.1 arcsec, and our normal galaxies are slightly larger, averaging 1.7 arcsec.

The disk galaxy evolution accretion models by Westera et al. (2002) show a radial color gradient in (V-I) of about 0.2 mag from center to edge at  $z=0$ , with a radial gradient of about 0.6 mag at  $z=1.3$ . The (V-I) colors of the central red dip and disk for our edge-on galaxy shown in Figure 1 are consistent with their model for  $z=0.25$ . However, our chain galaxy in Figure 1 matches none of the model color radial profiles, because no color gradient is present. This is further evidence that our chain galaxies are not exponential disk systems. Cowie et al. (1988) define a flat spectrum population of galaxies with integrated colors  $(B-I)_{AB} < 0.8$ . The majority of our chain, double, and tadpole objects have such a spectrum.

#### 4. Model

While chain galaxies have sizes, magnitudes, and colors comparable to faint normal late-type galaxies in the same field, the apparent dominance of the chains and other linear galaxies at faint magnitudes and their lack of exponential profiles are surprising. For random orientations, circular disk galaxies should have equal numbers in equal intervals of axial ratio ( $< 1$ ). However, for galaxies close to the surface-brightness limit of a survey, this is not the case. Edge-on galaxies that are not too optically thick have larger surface brightnesses than face-on galaxies of the same type because of the longer path lengths through edge-on disks. Edge-on galaxies have fainter total magnitudes because of their smaller projected areas. Thus face-on versions of these linear galaxies could be mostly below the surface-brightness detection limit of our survey.

The exponential nature of disks is best seen for nearly face-on galaxies where the line-of-sight extinction is small. Edge-on galaxies can have flat intensity profiles if extinction is important and we view only the near side of the disk. If the linear galaxies are edge-on bulge-less disks, then they could be either irregular with no intrinsic exponential light distribution, or exponential with a dust scale height comparable to the stellar scale height.

Edge-on galaxies have more extinction but their average surface brightnesses can still

be brighter than face-on galaxies because the extinction path length is usually larger than the disk thickness. Holmberg (1958) defined a corrected face-on surface brightness as the total flux divided by the square of the semimajor axis. If there is no internal extinction, then this is independent of inclination. The actual surface brightness is the flux divided by the projected area, rather than the deprojected area. The corrected face-on surface brightness is brighter than the actual average surface brightness by the extinction effect, and it is fainter than the actual average surface brightness by the ratio of axes.

Solanes, Giovanelli & Haynes (1996) determined the variation of corrected face-on surface brightness with axial ratio  $b/a < 1$  using the Holmberg definition  $\Sigma_H = m_0 + 5 \log a$  for semimajor axis  $a$  in arcsec. Here  $m_0$  is the total magnitude corrected for foreground Milky Way absorption. Solanes et al. obtained the result  $\Sigma_H = \Sigma_0 + k \log(b/a)$  where the slope of the relation is  $k = -0.9, -0.9, -1.3, -1.3$ , and  $-1.4$  for Hubble types Sa, Sab, Sb, Sbc, and Sc, respectively. This variation with  $b/a$  is from extinction alone, indicating that inclined galaxies are more heavily self-absorbed. The actual average surface brightness is  $\Sigma_a = m_0 + 2.5 \log(ab)$  for projected area  $ab$ . Thus the actual  $\Sigma_a$  is related to the Holmberg  $\Sigma_H$  as  $\Sigma_a = \Sigma_H + 2.5 \log(b/a)$ . The dependence of actual average surface brightness on projected axial ratio is  $\Sigma_a = \Sigma_0 + k' \log(b/a)$  where  $k' = k + 2.5$ . The first term,  $k < 0$ , is from internal extinction and the second term, 2.5, is from the ratio of the areas of the projected ellipse to the deprojected circle. For the five Hubble types,  $k' = 1.6, 1.6, 1.2, 1.2$ , and  $1.1$ , respectively. As  $(b/a)$  decreases for more highly inclined galaxies, the actual surface brightness in mag arcsec $^{-2}$  decreases and surface brightness becomes brighter. This makes galaxies close to the surface brightness limit of a survey more easy to see if they are highly inclined.

Figure 8 shows a radiative transfer model of a disk with an exponential profile in 4 scale lengths for both emissivity and absorption. The top, middle, and bottom curves of each type have perpendicular opacities to the center midplane equal to 0.33, 1.33, and 1.77 optical depths (1.33 gives an absorption rate of 1.5 mag/kpc at 2 scale lengths out in the disk if the scale length is 3 kpc, and this is typical in V band for a modern galaxy). In the bottom figure, the solid lines are the radial profiles along the midplane for the disk viewed edge-on, the dashed lines are along strips parallel to the midplane but displaced by one disk thickness scale length (i.e., off-axis strips), and the dotted lines are for face-on versions of these same disks. Brightness is normalized by setting the volume emissivity to 1 in the center midplane. The natural log of the intensity is plotted; this is approximately the same as a magnitude scale but with brighter emission more positive in this case. The model assumes a vertical profile of both emissivity and dust that is Gaussian with a 1/e half-thickness equal to 4% of the disk scale length. Evidently, the midplane and off-axis profiles are nearly flat, especially for high extinctions, and the face-on profile is exponential with a surface brightness that is

lower by 2-3 mag. Thus it is difficult to tell if an edge-on galaxy has an exponential disk when the dust thickness is comparable to the stellar thickness. If the dust layer is thinner than the stellar layer, as in modern galaxies, then the midplane alone may be dark but the exponential profile will still appear along a major-axis strip that is displaced from the midplane.

The ratio of the upper two opacities in these curves, 0.75, is the same as the ratio of V to B extinction in the galaxy rest frame for a normal extinction curve (where  $A_V = 3E(B-V)$ ). This translates approximately to an extinction  $A_I \sim 3E(V-I)$  at the expected redshift of these objects. Thus the (V-I) color excess from extinction ( $= A_V - A_I$ ) for an edge-on disk of this type is the difference between the two nearby curves of each type in Figure 8, which is  $\sim 0.25$  mag. The large range of observed colors (V-I) in Figure 4 makes it difficult to tell if this small amount of extinction is present in our sample.

The top of Figure 8 shows the average integrated surface brightnesses of the same three galaxy models, now viewed at inclination angles given by the log of the ratio of axes,  $a/b > 1$ , on the abscissa. The surface brightness becomes large at high axis ratio because that projects the longest path length through the stars, even with interstellar dust. The average slope of this relation in the figure,  $k' \sim 1-1.5$ , is about the same as the observed slope from Solanes et al. (1996) after conversion of their Holmberg surface brightness to actual surface brightness (see above). If the practical detection limit for the visual identification of a linear structure is one magnitude of surface brightness fainter than the edge-on value, as suggested by the shift between the peak for the chain galaxies and the detection limit in Figure 5, then Figure 8 gives us the expected range for the ratio of axes of these galaxies. This magnitude difference corresponds to an  $\ln(\text{average Intensity})$  that is 1 less than the peak on the right of Figure 8. In this case nearly everything that can be seen will have an axis ratio greater than 3-4, the corresponding value on the abscissa. The inverse of this ratio, 0.25 – 0.3, would be the fraction of all comparable galaxies that are detected. For this model, the chain, double, and tadpole galaxies could be edge-on late-type or irregular galaxies whose face-on counterparts are not obvious because they are below the surface brightness limit of the survey.

To check whether there could be a faint population of galaxies that are face-on versions of the chain, double, or tadpole galaxies, we searched the HST field of view for small clusters of emission clumps having about the same overall angular size and clump count as a typical chain galaxy. Figure 9 shows two examples. The colors of these clump clusters and their individual clumps are plotted in Figure 4 as crosses and plus signs, respectively, the average surface brightnesses are plotted in Figure 5, and the magnitudes of the clump clusters and individual clumps are plotted in Figure 6. Evidently, the integrated and clump properties are similar to those of the chains, doubles and tadpoles, but the average surface brightnesses

of the clump clusters are  $\sim 1$  mag arcsec $^{-2}$  fainter. The lowest contours in Figure 9 are  $1\sigma$  for the left-hand clump cluster, as in the contours of Figure 2, and  $0.5\sigma$  for the right-hand cluster.

A problem with the interpretation that chain galaxies are all edge-on clumpy disks is that some of them in this survey, such as the four shown in Figure 1, have average surface brightnesses that are  $\sim 10\sigma$  of the image noise. These examples are not close to the detection limit and yet no peripheral emission can be seen that resembles the rest of an edge-on disk. They would have to be highly inclined disk galaxies if this model is correct. Rotation curves or inclination statistics might eventually confirm this. Another problem is that the double and tadpole galaxies would look this way from nearly any orientation. They could already be face-on and we would not know it if the underlying galaxy is too faint to see. Because the double and tadpole galaxies have a peculiarity that cannot be transformed away by projection effects, the chain galaxies might have an intrinsic peculiarity too; i.e., they might really be chains even though this structure is dynamically unstable.

The normal edge-on galaxies in our sample have bulges like early-type galaxies and they have exponential profiles presumably because their gaseous and stellar disks have relaxed and their gas disks are thinner than their stellar disks. This relaxation makes sense for early-type galaxies because their evolution is faster than late-type galaxies. If the chains, doubles and tadpoles are disk galaxies too, then they either have no exponential profiles or their exponential profiles are hidden by dust, as shown in Figure 9. This would require their gaseous disks to be comparable in thickness to their stellar disks. Such a large scale height for dust in late-type galaxies is consistent with the very large star-forming regions that are seen in these galaxies, because the Jeans length in the ambient interstellar gas is usually comparable to the scale height.

## 5. Conclusions

We measured the properties of 127 linear galaxies with chain, double, and tadpole morphologies, as well as the properties of other linear objects that are normal edge-on spirals, out to I-band magnitude 27 in the HST ACS Tadpole field. We also measured 2 clump clusters that could be face-on versions of the chain galaxies. All of the objects contain similar blue clumps that are apparently massive star-forming regions, with masses up to  $10^9 M_\odot$ . The normal galaxies have centralized, red clumps that are probably bulges, unlike the linear galaxies which have few red clumps anywhere. The normal galaxies also have exponential brightness profiles, unlike the linears which are flat. The chain, double and tadpole galaxies dominate all edge-on galaxies in the field beyond an apparent magnitude of

~ 24.

We considered that most chain galaxies could be edge-on, late-type or low surface brightness galaxies that are close to the surface brightness limit of our survey. The late type explains the lack of a bulge, while the surface brightness limit explains the dominance of edge-on orientations (since edge-on galaxies have higher surface brightnesses than face-on galaxies). We cannot tell if the intrinsic stellar surface density profiles are exponential with obscuring dust layers or if they are intrinsically non-exponential. The clump clusters have non-exponential profiles because their light distributions are dominated by the clumps.

If the chain and other linear galaxies are edge-on clumpy disks, then a deeper survey should show more features in these galaxies, making them look more like normal galaxies, while a new set of linear galaxies should begin to dominate the field close to the new surface brightness limit. On the other hand, if chain galaxies look the same at higher sensitivity, then they are probably not edge-on disks but filaments in a more exotic and transient phase of galaxy formation. The total luminosity of a chain galaxy is comparable to the luminosity of a normal galaxy bulge in our sample, so if chain galaxies are unstable clumpy filaments (Cowie et al. 1995) then they could collapse into bulge-like objects, possibly providing seeds for normal galaxy formation.

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Fig. 1.— V-band image of a  $1' \times 1'$  field within the Tadpole ACS field shows several objects classified here as chain galaxies. (see f1.jpg)

Fig. 2.— Morphologies are shown in V band for (a) chain, (b) double, (c) tadpole, and (d) normal galaxy classes. The angular scales are shown by the axis tickmarks, which are separated by 10 pixels ( $= 0.5$  arcsec) for (a), (c), and (d), and 1 px ( $= 0.05$  arcsec) for (b). (see f2.jpg)

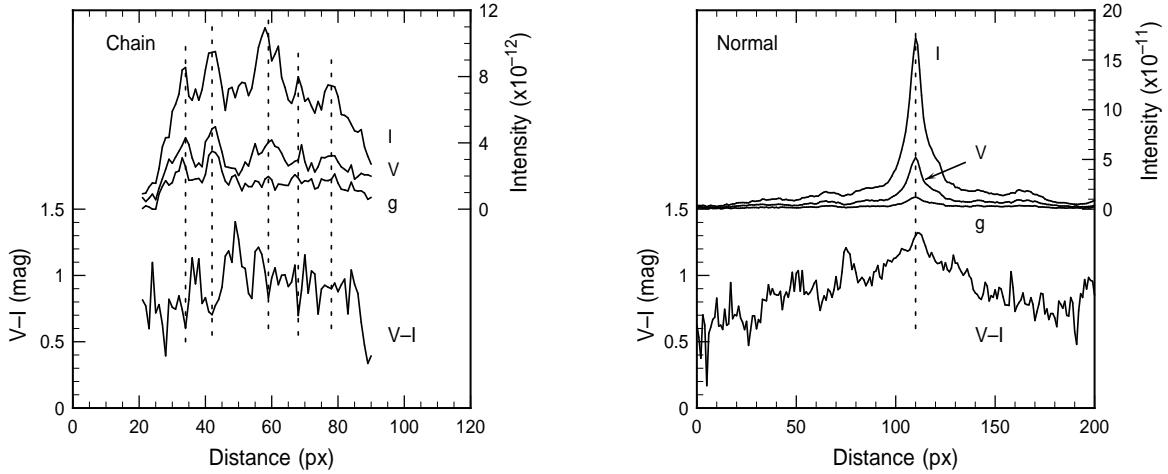


Fig. 3.— Radial profiles showing the intensity (top) in each of the three bands as a function of distance along the object (in px = 0.05 arcsec) and (V-I) mag (bottom) for a chain galaxy (left) and normal galaxy (right).

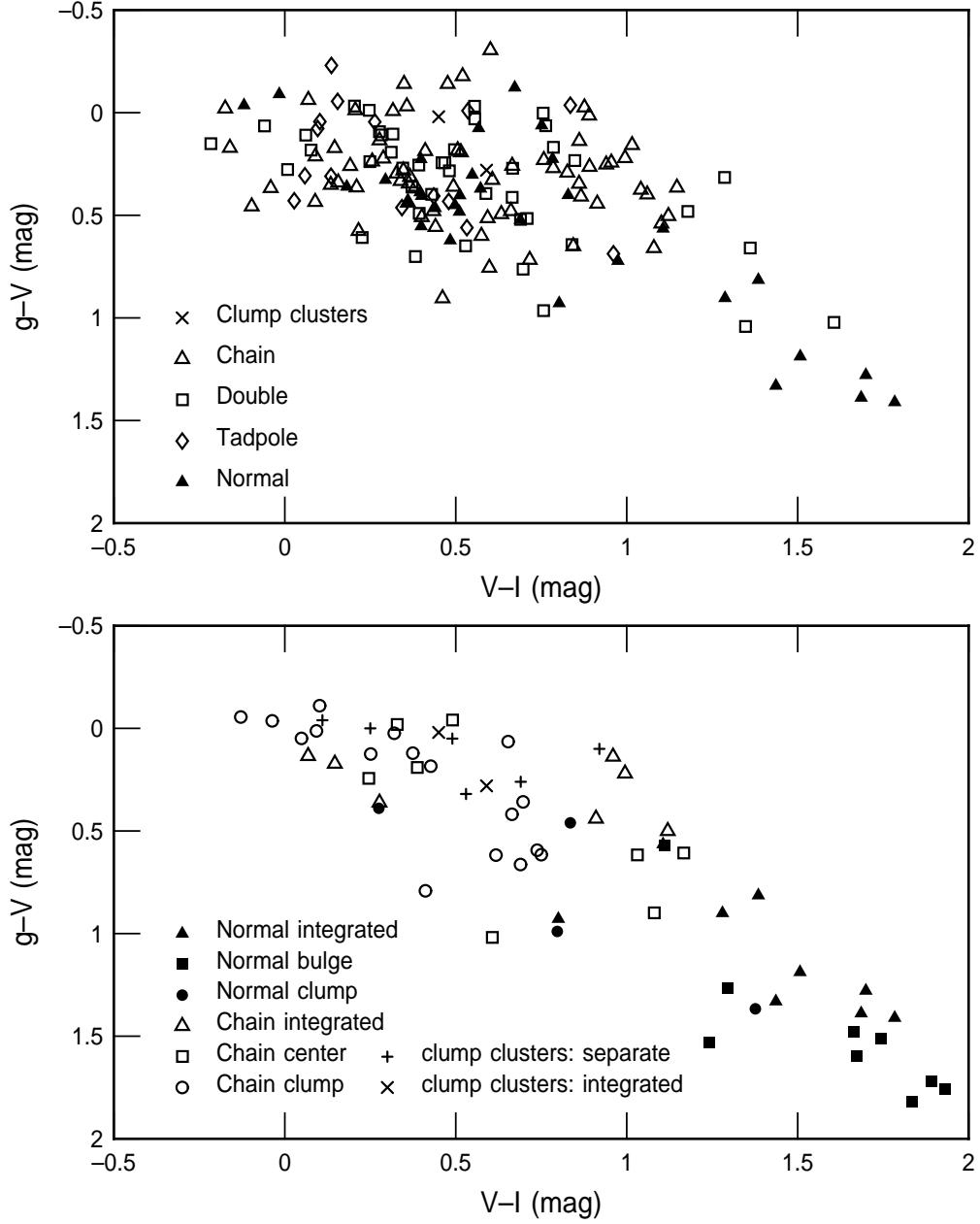


Fig. 4.— (top) Color-color diagram for whole galaxies, with open symbols for the integrated chain, double, and tadpole galaxies, and filled symbols for the integrated normal galaxies. The two crosses are the clump clusters in Fig. 9. (bottom) Color-color diagram with filled symbols for a representative sample of integrated normal galaxies, their central peaks and off-center clumps, and open symbols for a sample of integrated chain galaxies and their central and off-center clumps. The crosses and plus signs are for the clump clusters in Fig. 9.

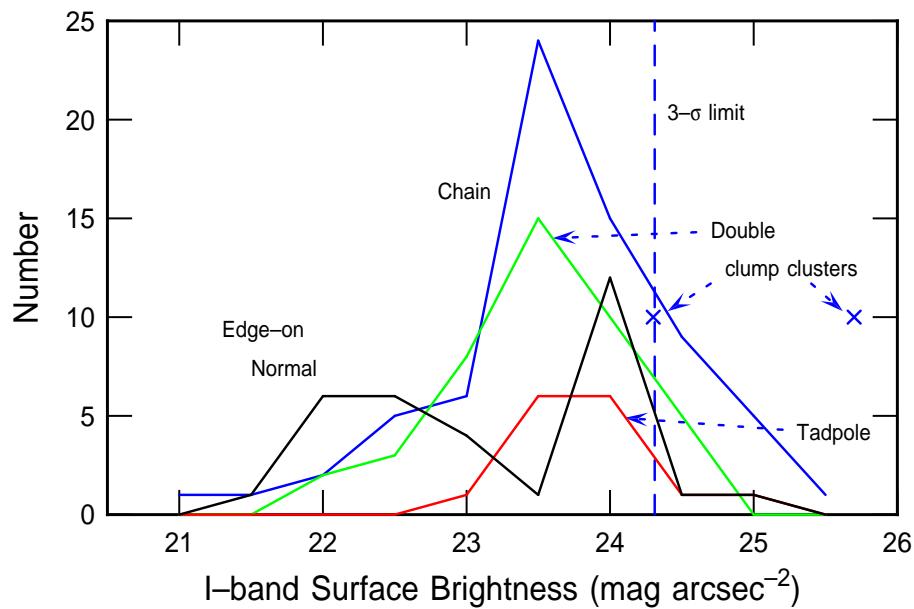


Fig. 5.— Distribution of surface brightness for various morphologies. The vertical dashed line is the  $3\sigma$  detection limit. Chain galaxies dominate our sample at low surface brightness. The galaxy count drops close to and beyond the  $3\sigma$  limit. The two crosses indicate the average surface brightnesses of the clump clusters shown in fig. 9.

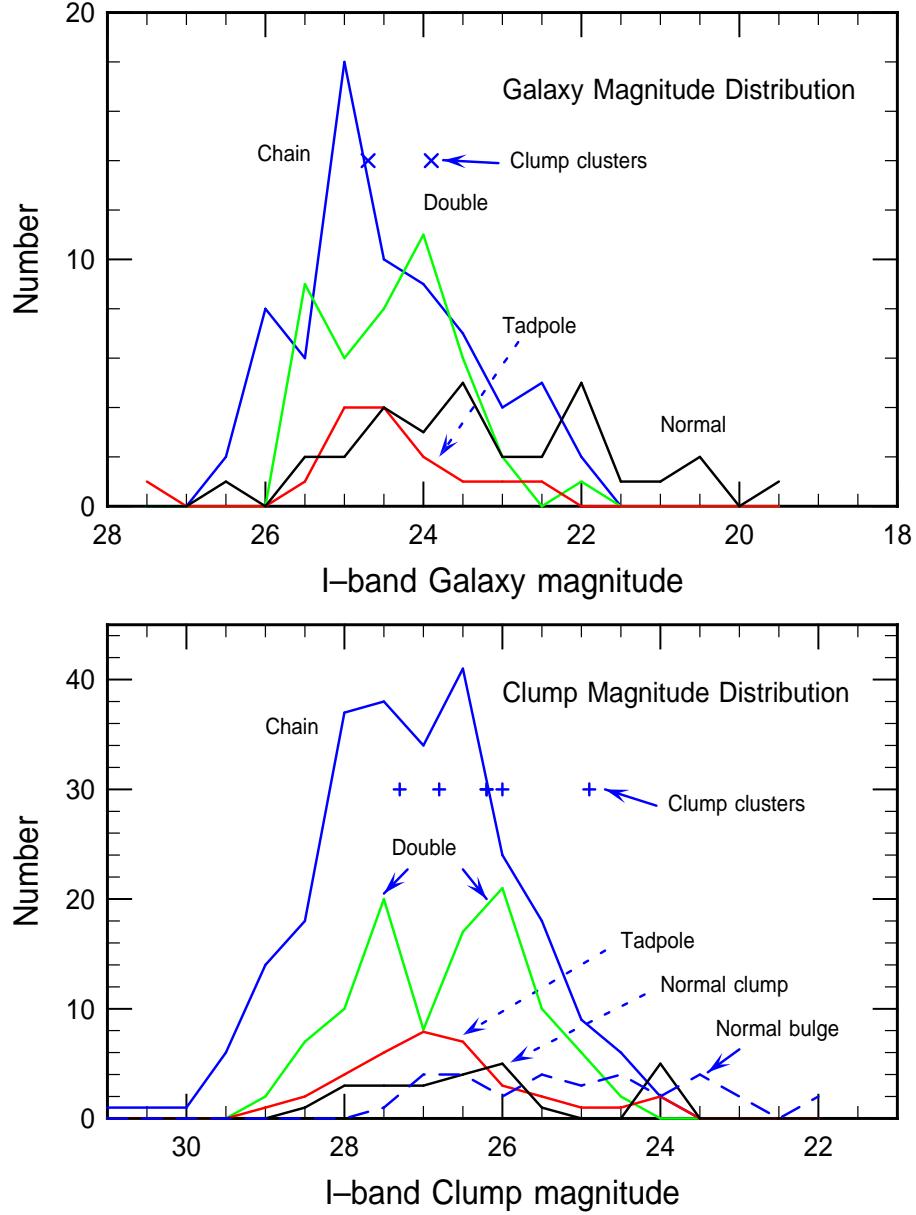


Fig. 6.— Distribution of I-band magnitude of whole galaxies (top) and individual clumps (bottom). Central clumps in the normal galaxies are brighter than their non-central counterparts and brighter than most of the clumps in the linear galaxies. Whole galaxies are brighter than the clumps by  $\sim 3$  mag, and most normal edge-on galaxies are brighter than the chains, doubles, and tadpoles by  $\sim 2$  mag. The average brightness of a whole galaxy of the chain, double or tadpole type is comparable to the average brightness of the bulge in a normal edge-on galaxy. The plus symbols are the clumps in the clump clusters shown in fig. 9.

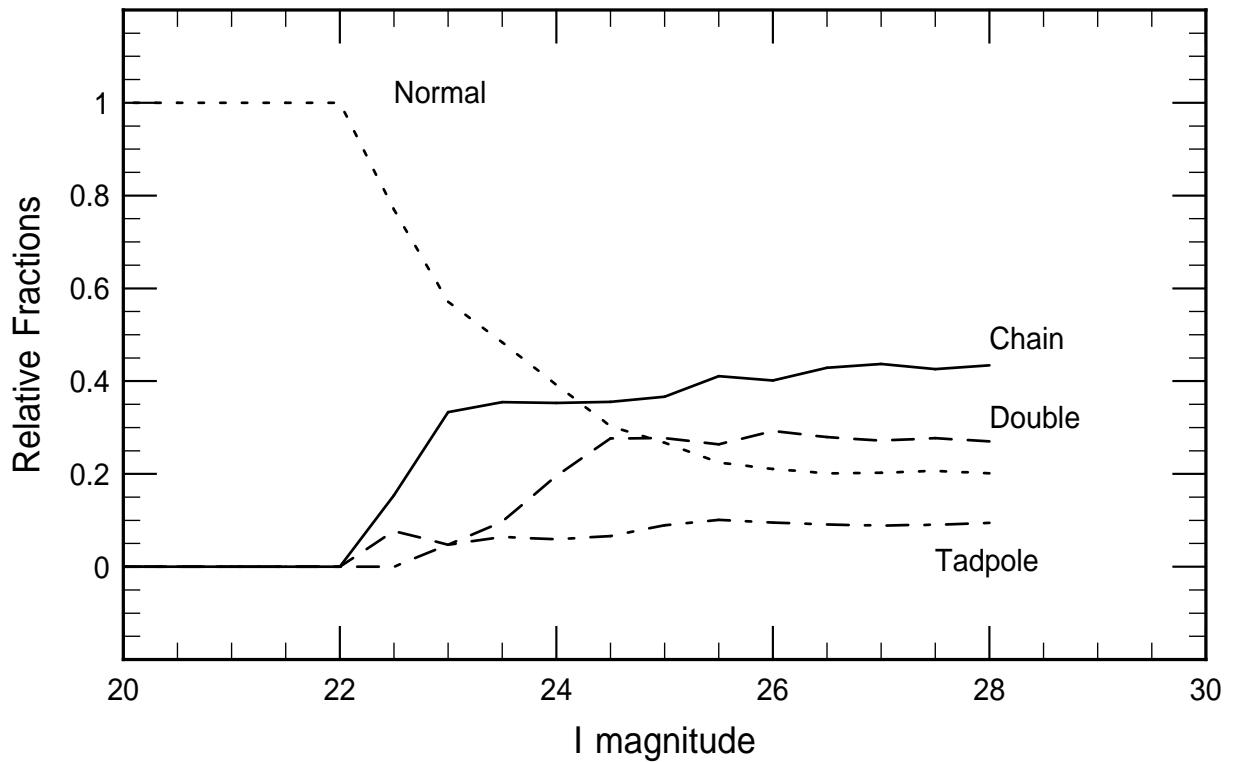


Fig. 7.— The fraction of galaxies with a given morphology is shown as a function of I-band magnitude. The normal galaxies dominate the bright end; beyond magnitude 24, the chain galaxies dominate. The fractions are approximately constant beyond this magnitude.

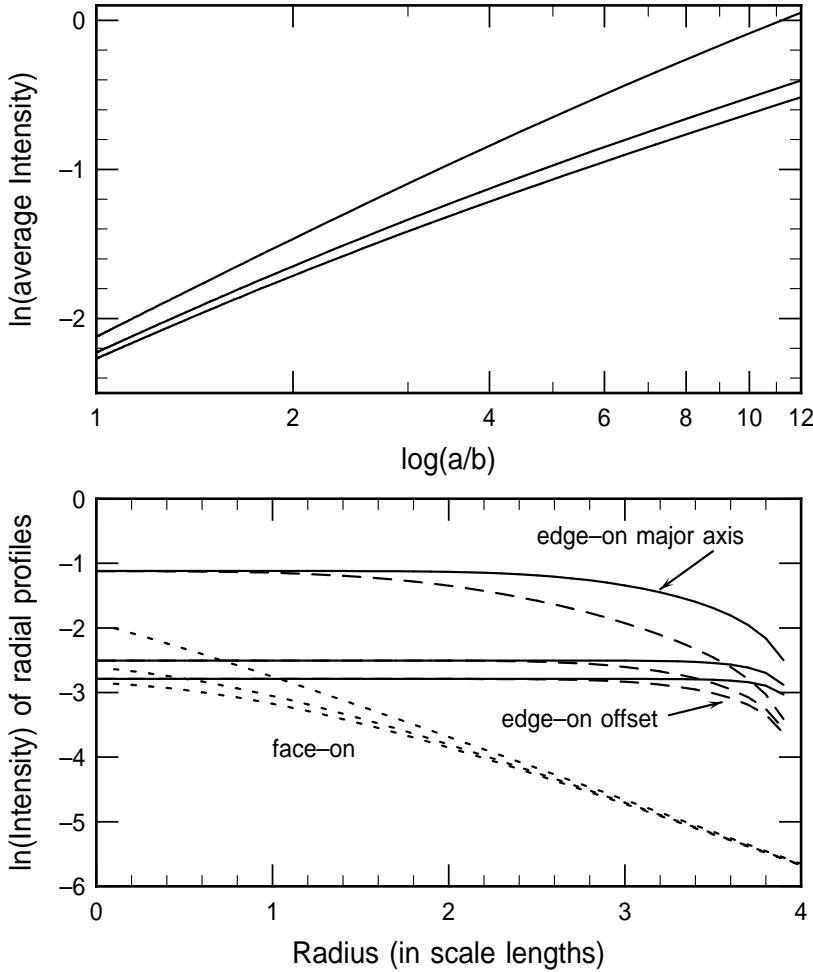


Fig. 8.— The bottom panel shows radiative transfer solutions of the average intensity along the major axis of a  $90^\circ$  inclined dusty disk (solid line) and along a line displaced from this by one disk scale height (dashed). The dotted line is the brightness profile for a face-on version of the same galaxy. The three cases have perpendicular extinctions to the midplane at the galaxy center equal to 0.33, 1.33, and 1.77 optical depths. The top panel shows the average surface brightness of a disk galaxy with an inclination given by the ratio of axes on the abscissa. Late-type galaxies close to the surface brightness limit of a survey will be mostly edge-on.

Fig. 9.— Two clump clusters that could be face-on versions of chain galaxies. The tic marks are separated by 10 pixels ( $= 0.5$  arcsec). The contours are  $1\sigma$  for the left-hand clump cluster, as in Fig. 2, and  $0.5\sigma$  for the right-hand cluster. The objects have the same angular size and clump properties as the chain, double and tadpole galaxies, but they are 2 dimensional rather than linear. (see f9.jpg)

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<http://arXiv.org/ps/astro-ph/0401364v1>